# Testing & Analysis of Pipeline Encapsulation Technologies

**Team Members:** University of Colorado Boulder
Cornell University
Gas Technology Institute
University of Southern Queensland

## Project Vision

Define performance metrics required by regulators and utilities to support commercialization of REPAIR technologies.
Establish a framework to evaluate & validate 50-year design life for pipe-in-pipe (PIP) solutions.

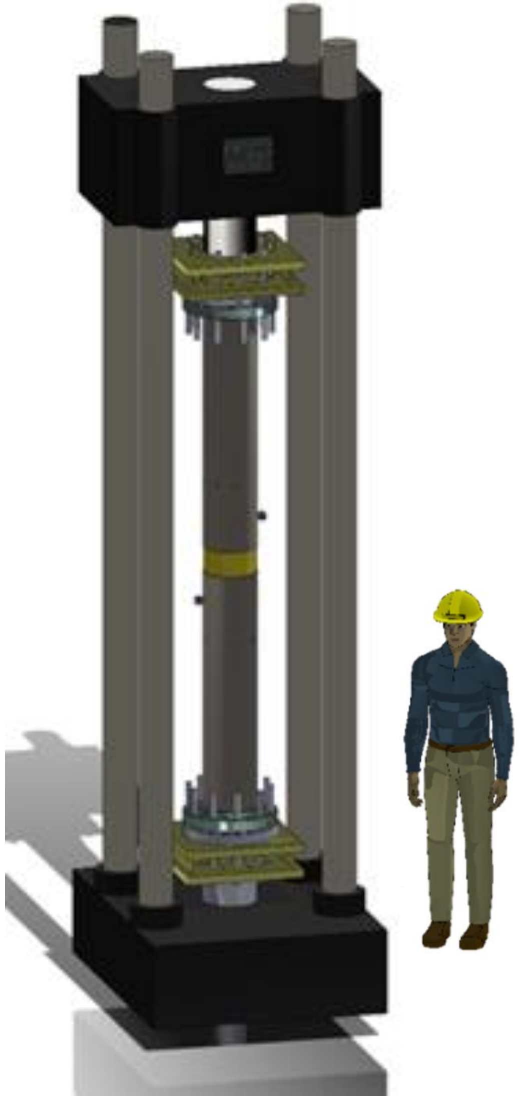

| | |
|---|---|
| Total Project Cost: | $5.65M |
| Length | 36 mo. |

# Testing and Technology Update: Outline

- Technical Review (22 min)
  I. Technology concept overview
  II. T&A Team and Roles
  III. Project Objectives and Milestones
  IV. POs: Define and Modeling
  V. External Testing & Specimens
  VI. Internal Testing & Specimens
  VII. Looking Forward
- Feedback & Questions (8 min)

# Concept Overview

- Develop a data-driven framework of physical testing and modeling to ensure REPAIR **technologies meet stakeholder requirements**
- Validate a **50-year design life** for innovative pipe-in-pipe (PIP) systems by developing numerical, analytical, and physical testing protocols.
- Merged attributes of each approach to deliver a **comprehensive framework** for PIP technologies composed of a variety of materials and deposition methods.
- Characterize failure modes and establish **performance criteria** for pipe replacement technologies to support recommendations for PIP material properties suitable for acceptable design-life performance.
- Establish standard protocols and methods needed for **regulatory approval** of REPAIR technologies



# The Testing & Analysis (T&A) Team

Center for Infrastructure, Energy, and Space Testing
UNIVERSITY OF COLORADO BOULDER

Brad Wham, Shideh Dashti, Mija Hubler, Morgan Ulrich, Patrick Dixon, Jacob Klingaman, & team

Cornell University

Tom O'Rourke, Jim Strait, & team

- Development, calibration and performance of <u>external load/deformation</u> testing

gti

Khalid Farrag, Dennis Jarnecke, Marta Guerrero Merino, & team

- <u>Internal loads and deformations</u> assessment; internal pressure and materials testing

UNIVERSITY OF SOUTHERN QUEENSLAND

Allan Manalo, Karu Karunasena, Tafsirojjaman, Cam Minh Tri Tien, Ahmad Salah, Shanika Kiriella, & team

- <u>Numerical and analytical modeling</u> of Performance Objectives, material properties, and correlations with physical test results

Development of protocols, documentation, & standards

**<u>T&A Team Contact:</u>**
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# Project Objectives and Milestones

- FY 2022 Q1 focus:
  - M1: Submitting review documents: State-of-the-art technology review of repair systems and initial AHP
  - M2.2: Continuing to develop fundamental PO models
  - M2.3: Validating FE models for cross sectional ovalization, 4-point bending deflection and maximum displacements, axial deformation
  - M2.4: Calibrating FE Models
  - M3: Refining internal and external test plans and conducting bending test, internal pressure test, and permeation test with known industry materials

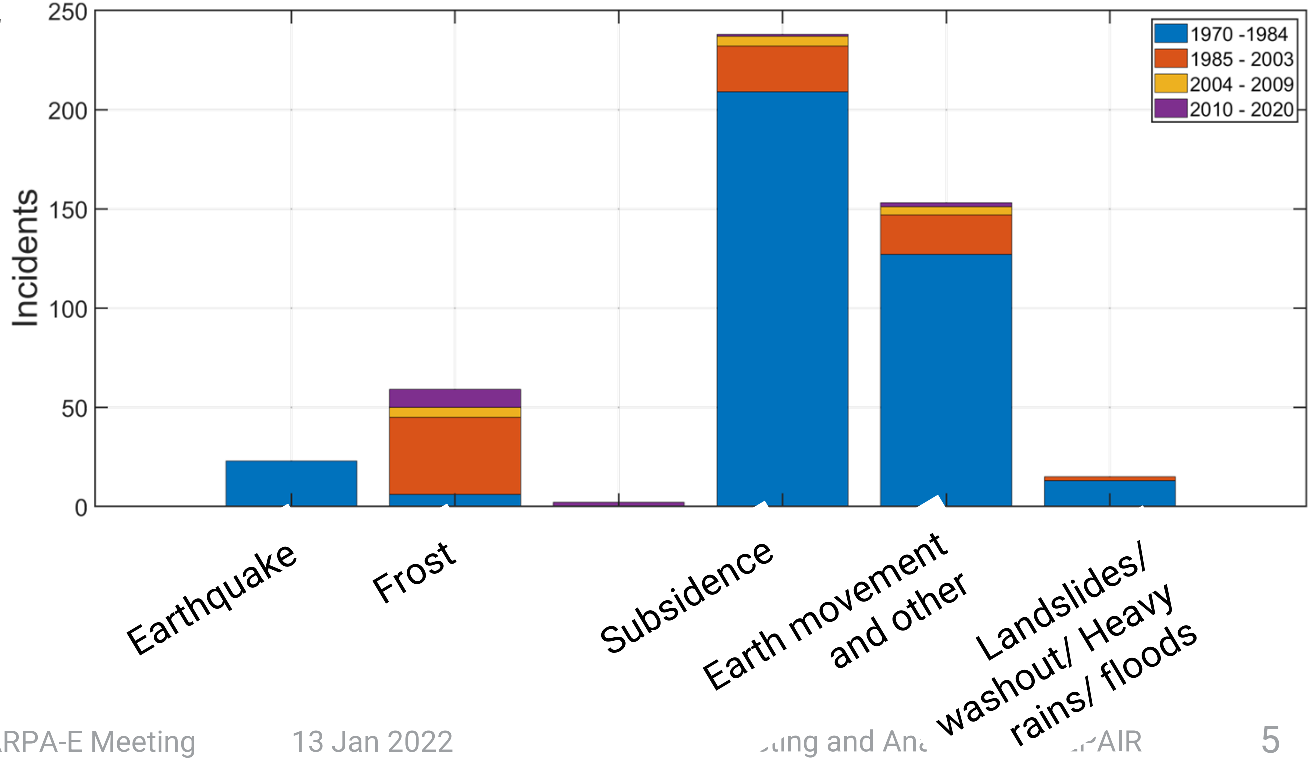
- Coordination of test specimens 2022 through 2023
  - M4: For the T&A team to testing milestones, developers must deliver lined samples no later than **April 2023 – *preferably sooner***
  - T&A team will provide pipe samples to developers for lining in advance, exact date TBD as we collect legacy CI pipes and fabricate steel pipes.

# Task 1: Identify Performance Criteria & FMs

Kozman, 2020.

- M1.1. Literature Review
  - Development of a Testing and Analysis Framework for Validation of Rehabilitating Pipe-in-pipe Technologies: NASTT 2022 No-Dig Show
  - State-of-the-art technology review of repair systems: Potential Failure Modes of Pipes and PIP
  - Important messages from this work:
    - (1) external loads are the major cause of incidents of gas distribution pipes
    - (2) natural causes that are associated with lateral deformation (bending) of pipelines are a major cause of incidents in legacy cast iron pipes

Figure 1. Spiral cracking at an unrestrained joint on Project 1



# Task 1: Identify Performance Criteria & FMs

- M1.0. Full list of Performance Objectives [T&A Focus: Mechanical performance of PIP Repairs,  ~80% POs]

| PO No. | Performance Objectives | Example Sources | Potential Failure Modes |
|---|---|---|---|
| **PO1** | Cyclic in-service surface loads | Overhead traffic or other surface loads | Fatigue failure in bending, outer fiber stress in tension (rupture) or compression (buckling) |
| **PO2** | Deflection (lateral deformation) | Adjacent excavation, subsidence, frost heave, undermining | Failure due to axial stresses, buckling, cross-section ovalization |
| **PO3** | Cross-sectional stiffness (ovalization) | External pressures, surface load, deflection (bending) of the pipeline | Ring collapse, delivery otherwise compromised by excessive/adverse ovalization |
| **PO4** | Axial deformation (displacement) | Thermal Loading (expansion/contraction) seasonal temp. changes | Damage/failure due to axial stresses, buckling, pinching, fracture of PIP. Detachment from host at termination point. |
| **PO5** | Circumferential (hoop) stress | Internal pressure, pressure fluctuations | Burst - failure due to tensile stress, stretch of material leading to leakage |
| **PO6** | Puncture/impact | Improper excavation, host pipe fracture, other external force | Puncture, drop weight, reduction in pressure capacity |
| **PO7** | Compatibility with current/future gas | Internal gas | Chemical degradation, excessive permeation |
| **PO8** | Debonding at PIP/host pipe interface | Differences in thermal expansion, mechanical loads | Gas-back tracking, leakage and delivery compromised, detachment at termination points, potential ring collapse |
| **PO9** | Service connections | Existing Infrastructure, abandoned and/or in-service connections | Failure at these stress concentrations, potential for differential movements also giving rise to failure at connections |

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<u>Additional Critical Considerations:</u>
~20% Performance Objectives

- Tapping for new service connections (PE, ST) or other similar sized components (e.g., drips, plugs)
- Existing tees, valves, threaded taps along pipe (e.g., blow offs, bag deployment, larger connections >3 in. diameter)
  - Intrusions into the pipe – greater than ~0.25 in.
- PIP installation impact on:
  - Elastomers, plastic pipe, seamed pipe
  - Various CI joint materials (e.g., jute/yarn/lead caulked, gasketed, mechanical)
  - Existing service connection taps of various materials (PE, ST, CI)
- Extreme temperatures
  - E.g., welding, exposed pipe at bridge crossing, proximity to buried steam line
- Additional Impact of high-water table
- Seismic Considerations
- Others?

# Task 2: Model PO and identify PIP properties

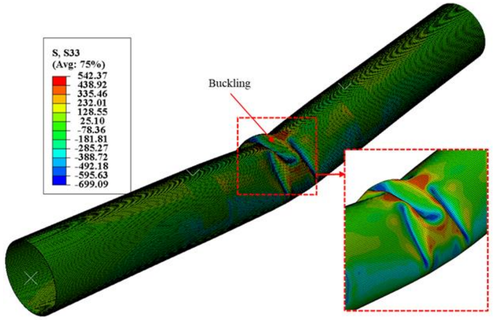
- M2.1. Initial screening models
- M2.2 Fundamental FM models
- M2.3. Initial Range of Material Properties

**Modelling efforts were focused on:**

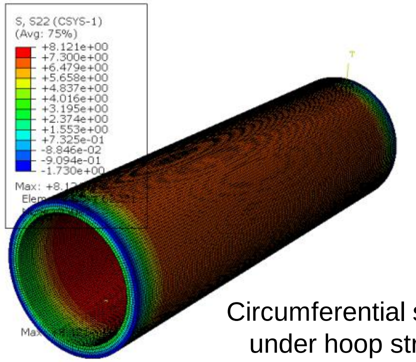
- **PO1.** Vibrational loads
- **PO2.** Deflection (lateral deformation)
- **PO3.** Cross-section ovalization
- **PO4.** Axial deformation due to thermal expansion/contraction
- **PO5.** Circumferential (hoop) stress due to internal pressure.
- **PO6.** Puncture of pipe system due to drop weight or external force.

**Description of the FE model for PIP:**

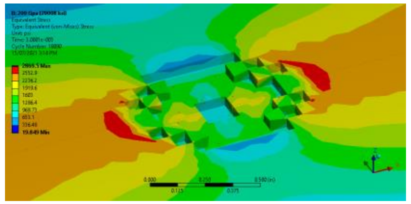
- <u>OD</u> = 307.8 mm (12.12 in) [12-inch Cast iron 21/45 pipe]
- <u>Wall thickness</u>: varied in the inward direction from 3.175 mm to 25.4 mm (0.125 in. to 1 in with increments of 0.125 in)
- <u>Elastic modulus</u>: 1GPa (145 ksi) to 200GPa (29,000 ksi)
- <u>Design Strain</u>: 0.002 for metallic systems [>70 GPa (10,153 ksi)] and 0.02 for polymeric systems [<24.5 GPa (3,550 ksi)].



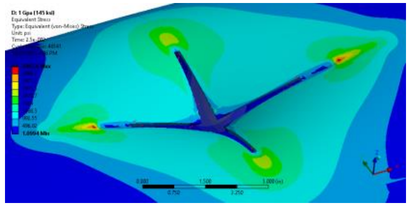

Compressive buckling of PIP systems under lateral deformation



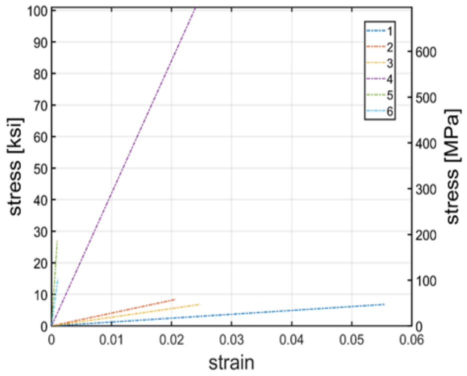

Circumferential stress under hoop stress



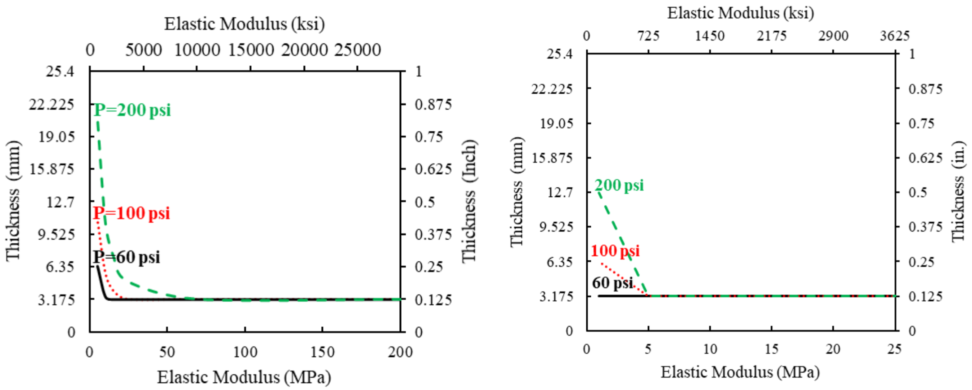
Impact damage mode for high modulus PIP materials.



Impact damage mode for low modulus PIP materials.




**Preliminary stress-strain curves of PIP up to elastic limit**




Minimum thickness requirement for different design internal pressure at strain of 0.002 (left) and strain of 0.02 (right)

# Task 1: Identify Performance Criteria & FMs

- M1.2. Analytical Hierarchy Process (AHP)
- **Appendix T1.2:** AHP of failure modes

**The AHP is implemented based on the below attributes:**

**PO1.** Target life cycle of one million cycles under vibrational loads caused by repeated overhead traffic loads equivalent to 17,350 N (3,900 lbf).

**PO2**. Lateral deformation under the design lateral load of 178 kN (40 kips).

**PO3**. Cross-section ovalization up to 5% and 10% diametric deflection.

**PO4.** Axial deformation (axial displacement) due to thermal expansion/contraction at a temperature change of 22℃ (39.6℉).

**PO5**. Circumferential stress due to internal pressure of 60, 100, and 200 psi.

**PO6.** Dent, metal loss or crack under impact loading caused by 1.5 in. (38.1 mm) semi-spherical drop weight of 1.1 pound (0.5 kg) at a height of 40 in. (1.02 m).

| PO Criteria | Vibration loads | | Lateral deformatio n | | Cross-section ovalization | | Axial deformation | | Internal Pressure (200 psi) | | Impact | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | PO1 | | PO2 | | PO3 | | PO4 | | PO5 | | PO6 | |
| Thickness (in.) | 3/8 | 1/8 | 1/2 | 1/8 | 1/8 | 1/8 | 1/8 | 1/8 | 1/2 | 1/8 | 3/8 | 1/8 |
| Elastic modulus (ksi) | 145 | 345 | 725 | 29008 | 145 | 145 | 145 | 145 | 145 | 725 | 145 | 725 |

Ranking when design internal pressure is 60 psi

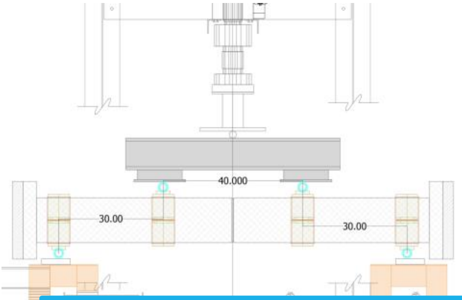
| Rank | PO |
|---|---|
| 1 | PO2 |
| 2 | PO6 |
| 3 | PO1 |
| 4 | PO4 |
| 5 | PO5 |
| 6 | PO3 |

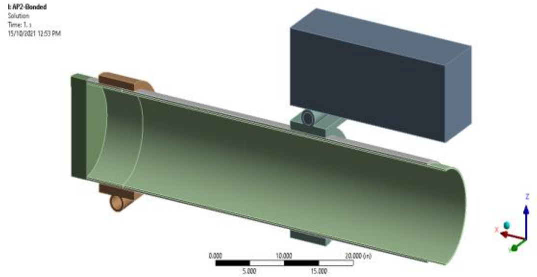
Ranking when design internal pressure is 200 psi

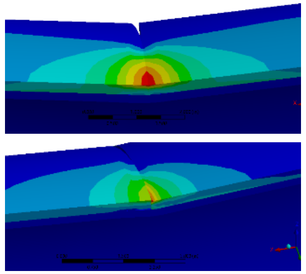
| Rank | PO |
|---|---|
| 1 | PO2 |
| 2 | PO5 |
| 3 | PO6 |
| 4 | PO1 |
| 5 | PO4 |
| 6 | PO3 |

# Task 2: Model PO and identify PIP properties

- M2.4. Calibrated FE Model
- M2.5 Comprehensive numerical/analytical studies of PIP

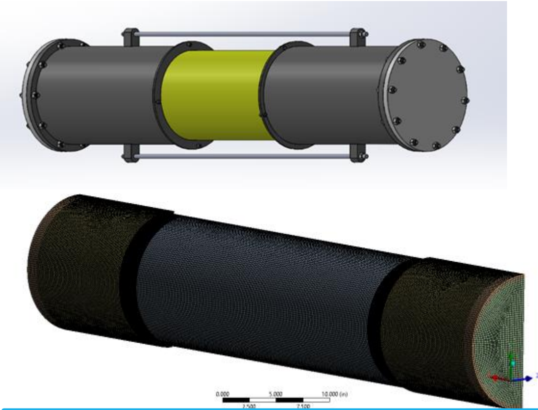


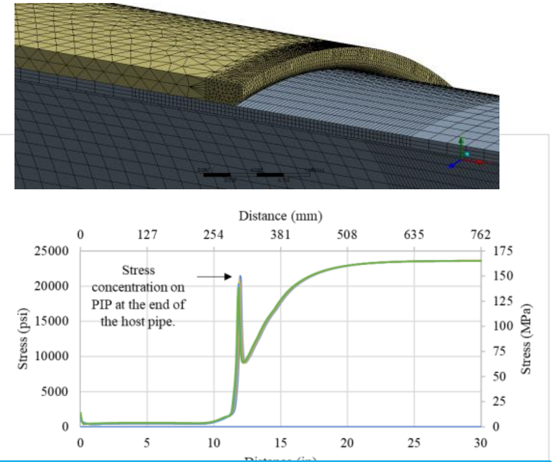





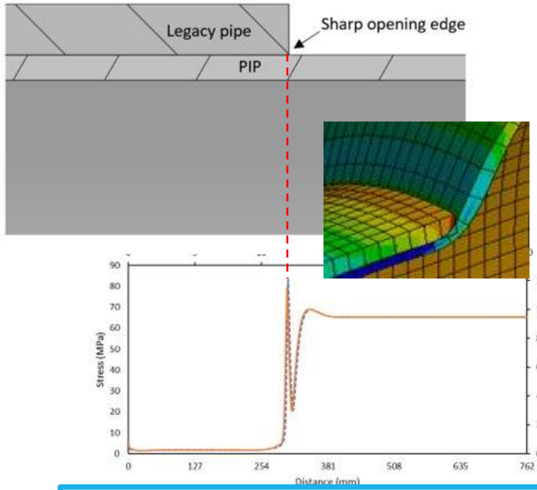
| Crack width mm (in.) | Bonded | Frictional 0.2 |
|---|---|---|
| 2.54 (0.1) | Tension failure on PIP at 200 kN (44,962 lbf) | Compression failure on host pipe at 90 kN (20,232 lbf) |
| 12.7 (0.5) | Compression failure on PIP at 150 kN (33,722 lbf) | Compression failure on host pipe at 75 kN (16,861 lbf) |
| 152.4 (6) | Compression buckling on PIP at 36 kN (8,093 lbf) | Compression buckling on PIP at 31.5 kN (7,082 lbf) |

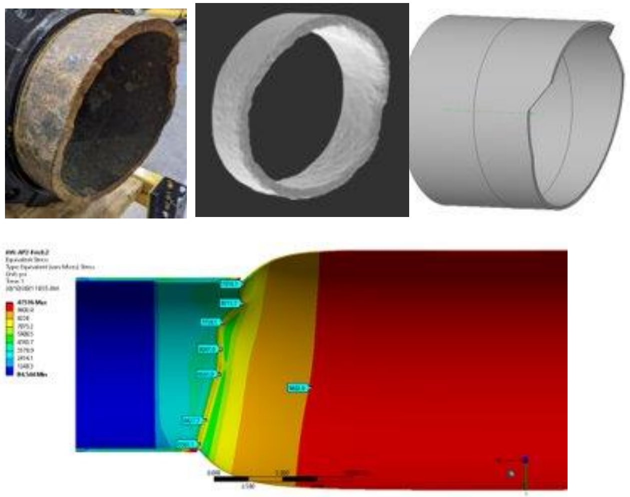
FE analysis of PIP and host pipe with various crack widths






FE analysis of PIP and host pipe under internal pressure



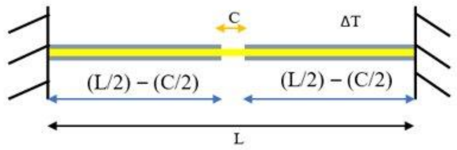



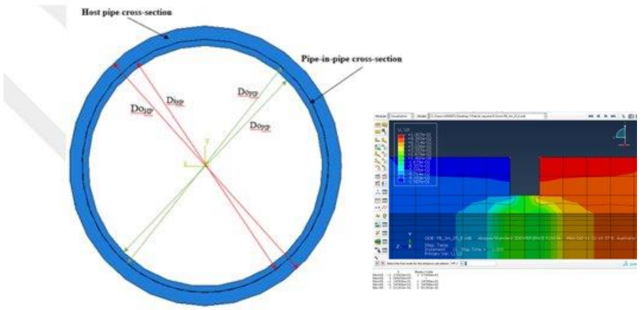
End effects of the host pipe on PIP under internal pressure

# Task 2: Model PO and identify PIP properties

- M2.5 Comprehensive numerical/**analytical studies** of PIP

## Thermal expansion of PIP with crack opening




$$P = \frac{\dfrac{\alpha_{HP}E_{HP}A_{HP} + \alpha_{PIP}E_{PIP}A_{PIP}}{E_{HP}A_{HP} + E_{PIP}A_{PIP}}\Delta T(L-C) + \alpha_{PIP}\Delta TC}{\dfrac{C}{E_{PIP}A_{PIP}} + \dfrac{L-C}{E_{HP}A_{HP} + E_{PIP}A_{PIP}}}$$

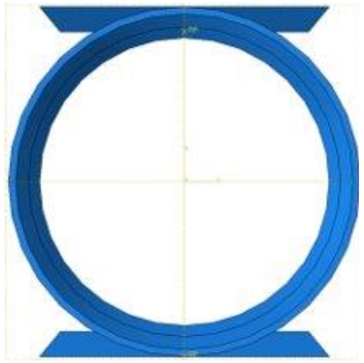
$\delta_{T_{HP}} = \frac{\alpha_{HP}E_{HP}A_{HP}+\alpha_{PIP}E_{PIP}A_{PIP}}{E_{HP}A_{HP}+E_{PIP}A_{PIP}}\Delta T\left(\frac{L}{2}-\frac{C}{2}\right)$ , for one segment of the host pipe

$\delta_{M_{HP}} = \frac{-P\left(\frac{L}{2}-\frac{C}{2}\right)}{(E_{HP}A_{HP}+E_{PIP}A_{PIP})}$ , for one segment of the host pipe

$\delta_{HP} = \delta_{T_{HP}} + \delta_{M_{HP}}$

The new crack width = C ± 2 × $\delta_{HP}$

## Analytical prediction of cross-section ovalization



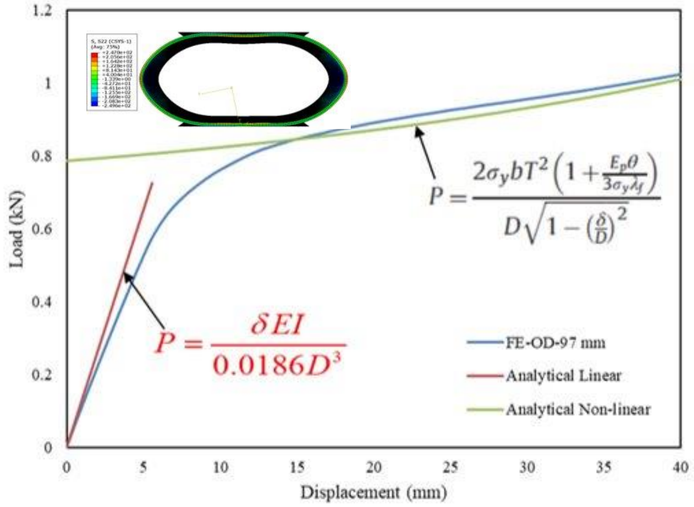
***Analytical prediction models:***

Compressive force for the linear part based on Hwangt [3]:

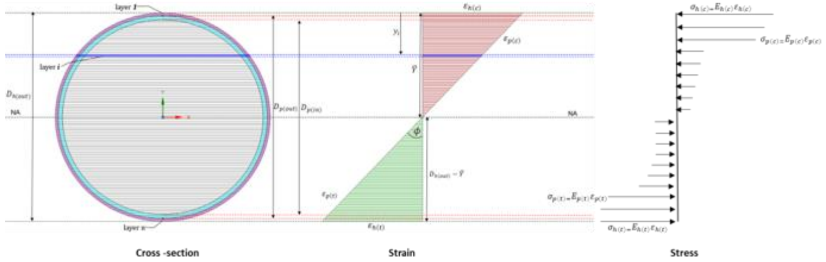
$$P = \frac{\delta EI}{0.0186D^3}$$

Compressive force for the non-linear part based on Redwood [4]:

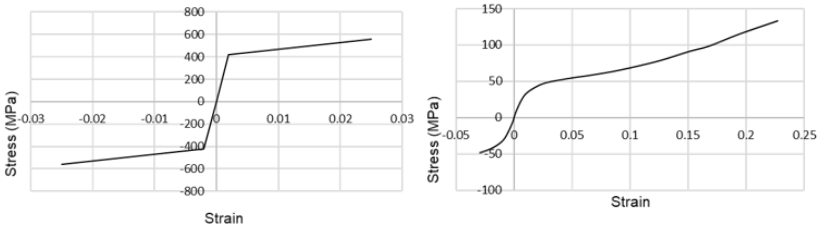
$$P = \frac{2\sigma_y bT^2\left(1+\frac{E_p\theta}{3\sigma_y A_f}\right)}{D\sqrt{1-\left(\frac{\delta}{D}\right)^2}}$$



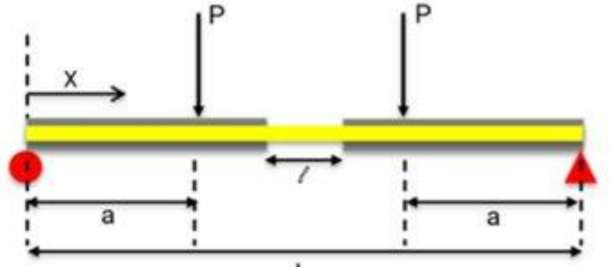

## Deflection of PIP and host pipe with crack




Basic assumption of Fibre Model Analysis




Constitutive material model of host pipe (left) and PIP (right)

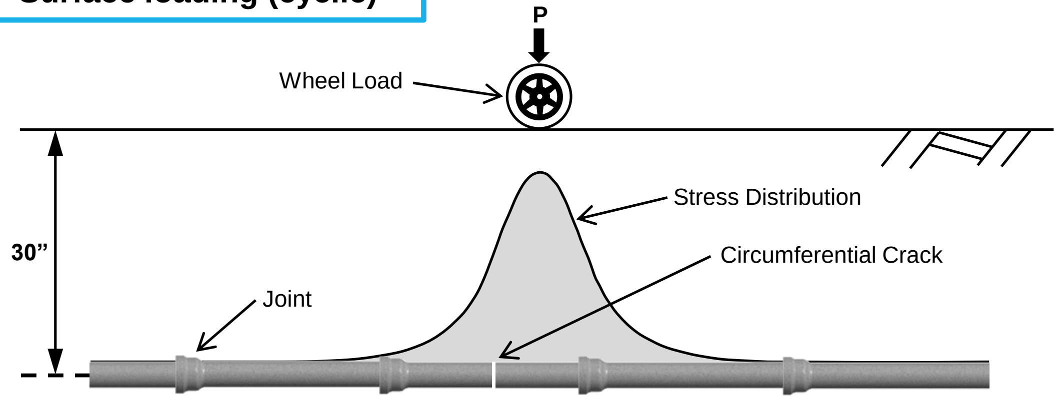


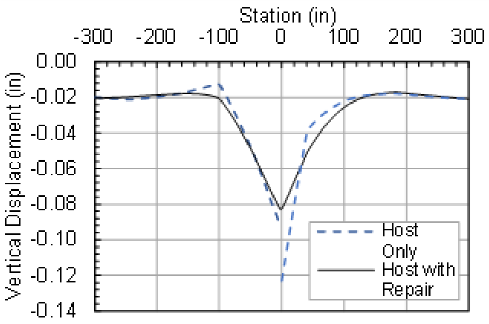

$$\Delta_{max} = \frac{Pa^3}{3(EI)_{eff}} + \frac{Pa}{8(EI)_{eff}}((L-l)^2 - 4a^2) + \frac{Pa}{8(EI)_{PIP}}(2Ll - l^2)$$

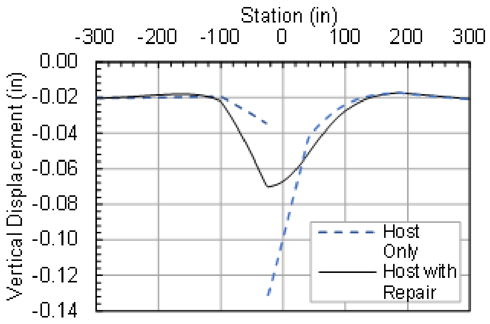
CHANGING WHAT'S POSSIBLE

# External load testing: design loads

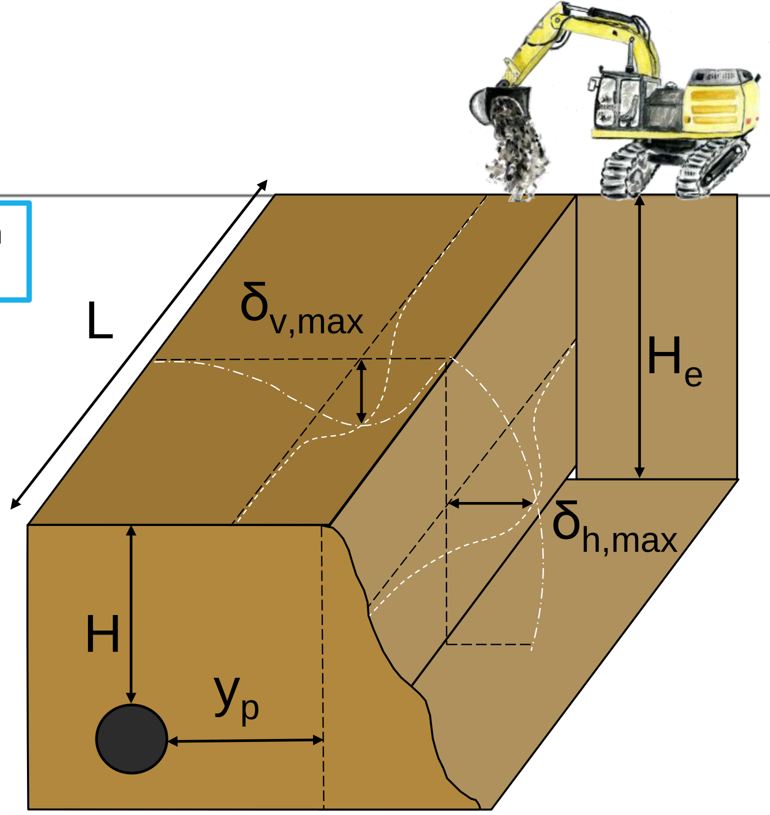
**Surface loading (cyclic)**

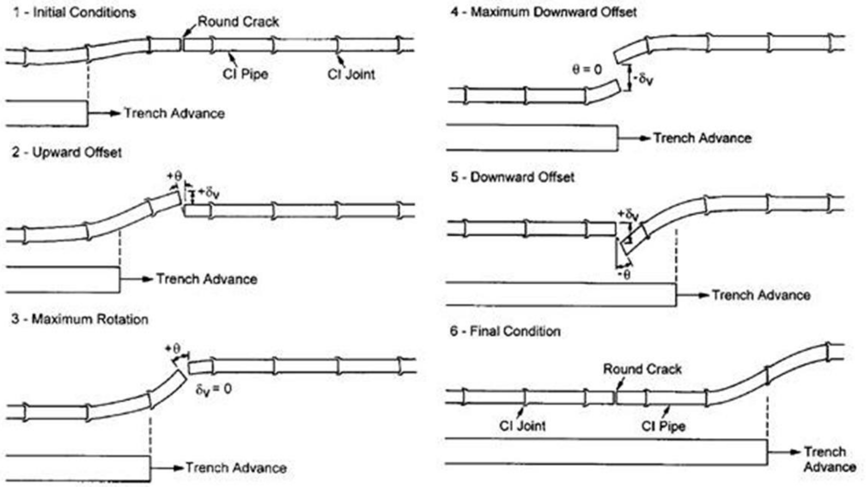



**Adjacent Excavation (lateral deformation)**

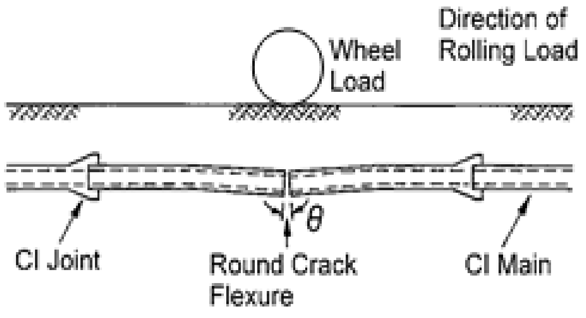
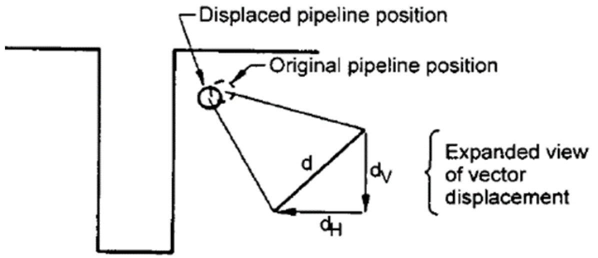


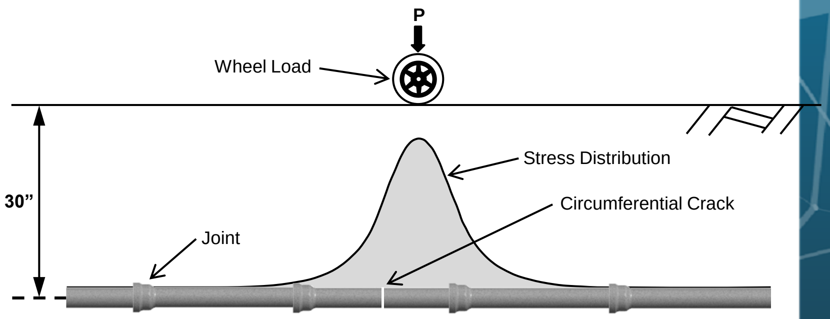

CHANGING WHAT'S POSSIBLE

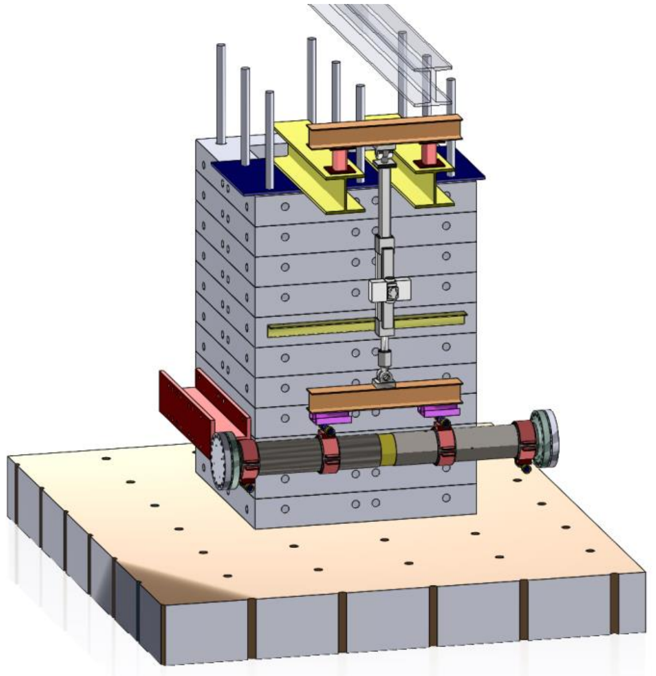
# T4: External Loading

- Task 4: <u>External Loading Tests</u>: Lateral Deformation

| Task | Hardware | Sub-Task | |
|---|---|---|---|
| T4. External load testing<br>(all external loads to be applied to each specimen in series) | T4.1. Four-point bending frames<br><br>*[POs 1, 2, 3]* | T4.1.1. Vibration/traffic loads (*PO1*)<br>[500,000 cycles]<br>- For compliant pipe linings spanning weak joints, the imposed vertical displacement was about 0.08 in. | <br>Stewart et al., 2015 |
| | | T4.1.2. Deflection (lateral deformation) (*PO2*)<br>[Large defl. + 100,000 cy.]<br>- For compliant pipe linings spanning weak joints, the imposed vertical displacement was about 0.20 in | <br>Jeon et al., 2004 |

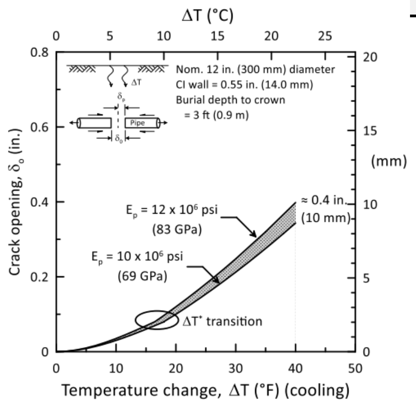
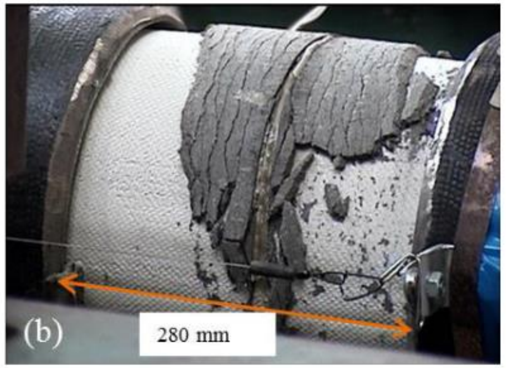
*FM3: cross-sectional ovalization to be monitored/assessed during lateral load application

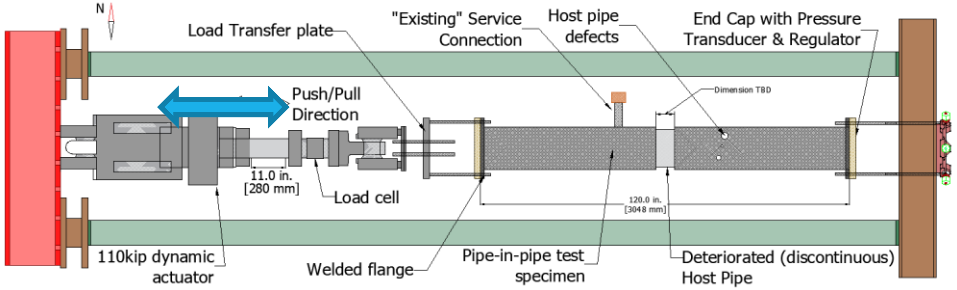


# T4: External Loading

- Task 4: <u>External Loading Tests</u>: Axial Deformation

| Task | Hardware | Sub-Task | |
|---|---|---|---|
| T4. External load testing<br><br>(all external loads to be applied to each specimen in series) | T4.2. Axial load frames<br><br>[*PO4,8*] | T4.2.1. Axial/thermal deformation (*PO4*)<br>[1 to 2 hr per cycle, 50 cycles]<br>- For compliant pipe linings spanning weak joints, the crack opening displacement was about 0.4 in | <br>Stewart et al., 2019 |
| | | T4.2.2. Bonding/de-bonding at coating/pipe interface (*PO8*)<br>Termination point capacity. | <br>Argyrou et al. 2017 |



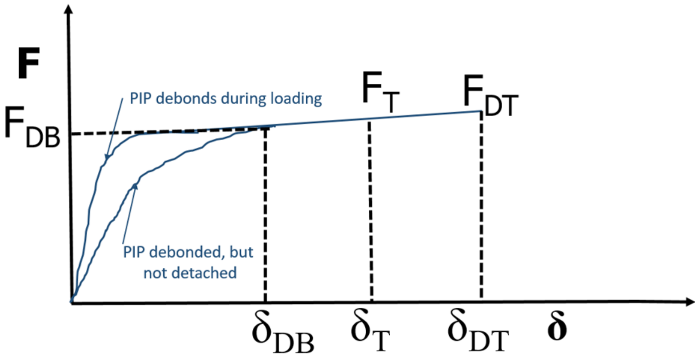
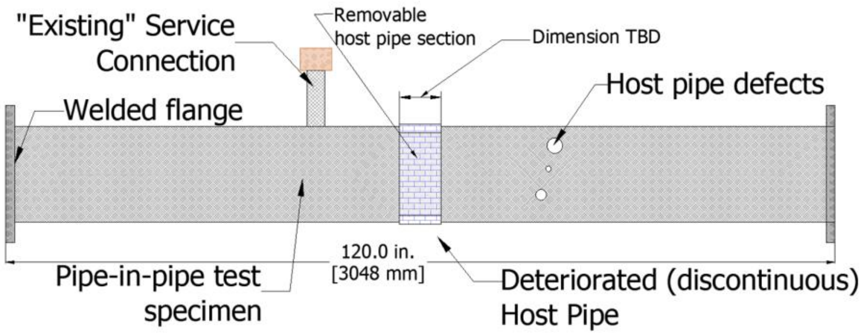
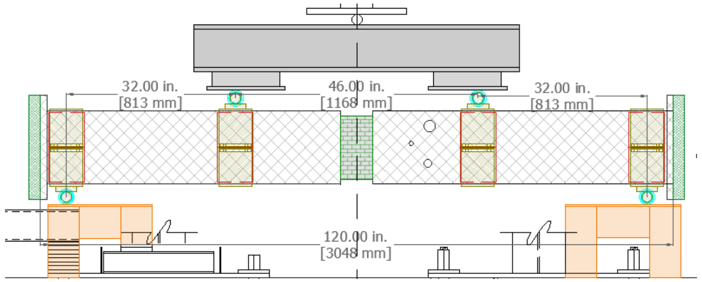




Figure 1. Force vs Displacement for a Relatively Low Modulus PIP

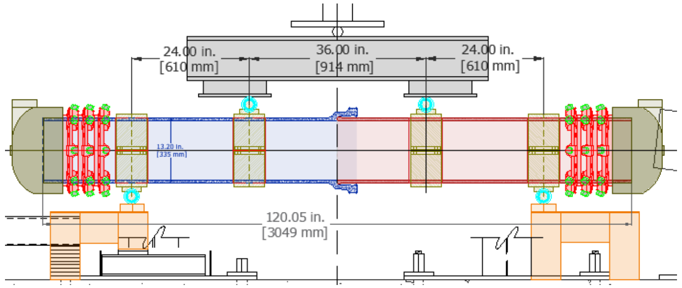
# T4: External Loading - Specimen Design

- **Fabricated Steel**
  - 2 or 3 specimens per developer
  - Capable of applying all loading conditions to PIP
  - Can accommodate various defects

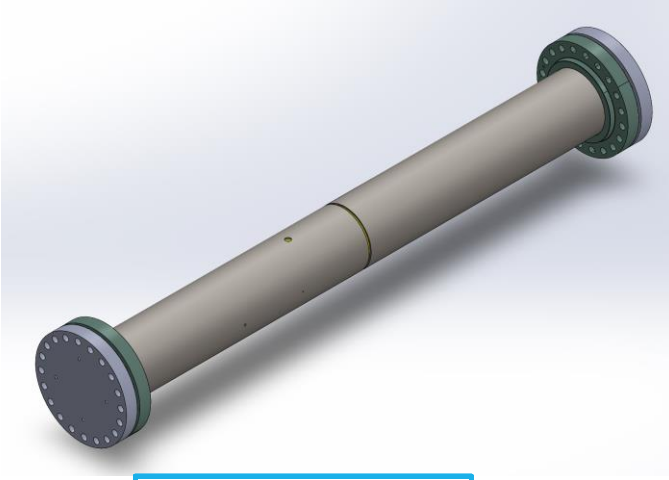



- **Legacy Cast Iron**
  - 1 or 2 specimen per developer
  - Round crack at center, Joint at center if available
  - May be limited in ability to apply axial deformation depending on several factors

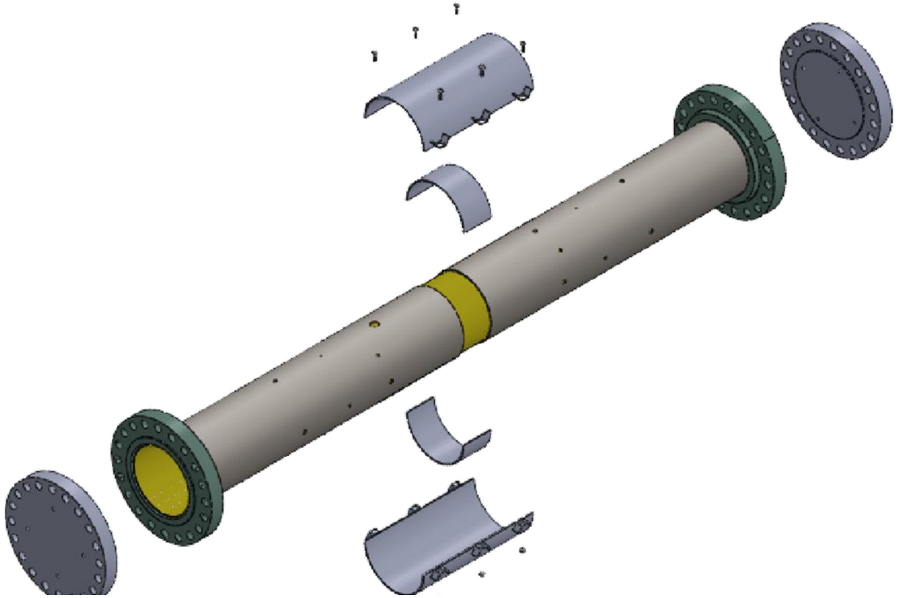


# T4: External Loading - Specimen Design (preliminary)

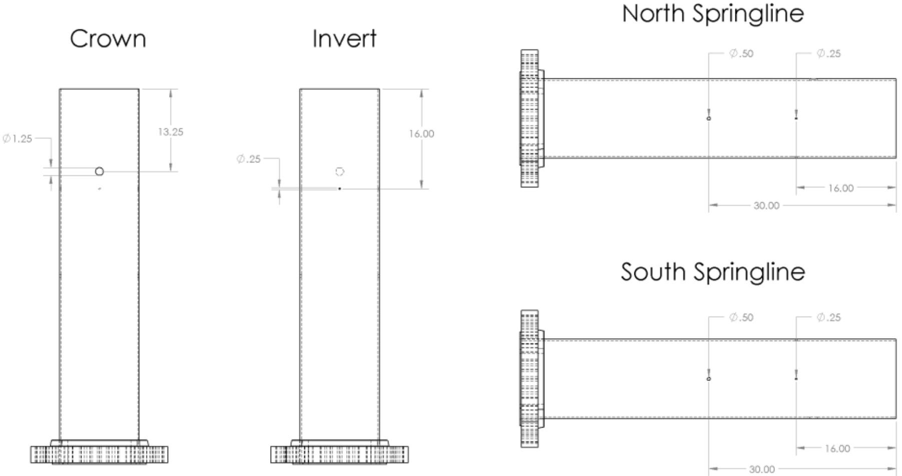


0.5 in. wide crack

6 in. wide crack



| Count | Dia. [in] | General Location | Distance of center from edge of pipe/crack [in] |
|---|---|---|---|
| 1 | 1.25 | Crown | 13.25 |
| 1 | 0.25 | Crown or Invert | 16.0 |
| 2 | 0.25 | Springlines | 16.0 |
| 2 | 0.50 | Springlines | 30.0 |



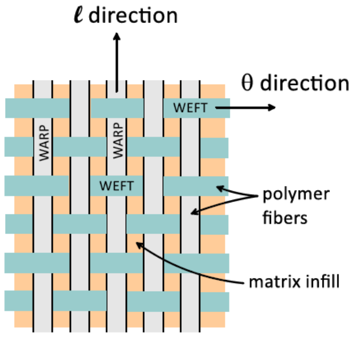
# Steel Pipe Preparation

# Known Material Testing (Sanexen) Steel Host Pipe

## ALTRA10/10X
## Structural Liner Technical Specs

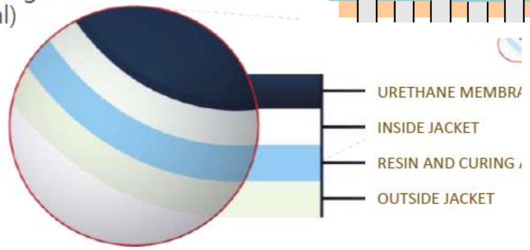
**A Composite Material:**

- Woven polyester fiber jackets
- Internal watertight polymeric membrane
- Thermosetting resin impregnation (which upon curing gives its structural properties to composite material)

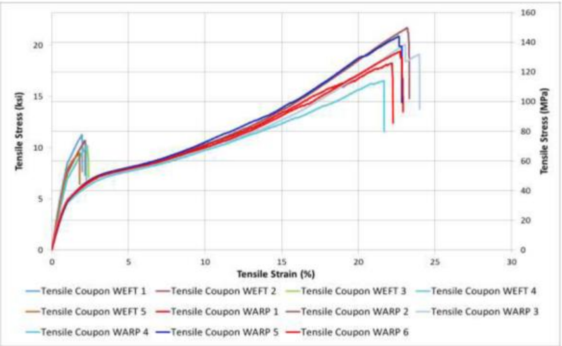



→ Certified by NSF to NSF/ANSI Standard 61 and UL

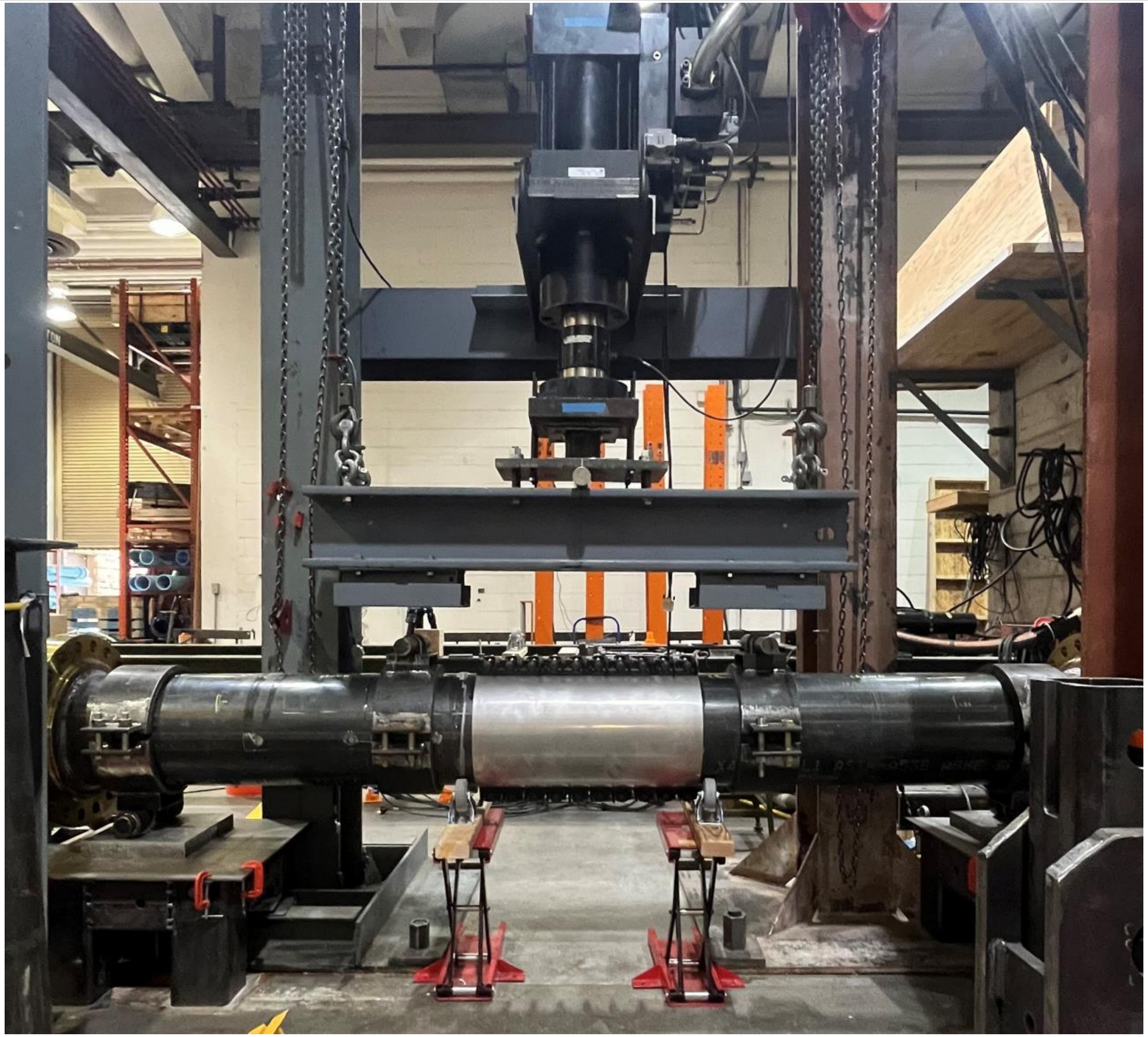
→ Exceeds ASTM F1216 and ASTM F1743 Standards




- **Diameters:** 100 to 600 mm (4 to 24 in)
- **Design Pressure:** 150+ PSI
- **Installation Length:** Up to 300 m (1,000 ft) between 2 access pits
- **Installation Method:** Pulled in place through the host water main (cure time/temp: 90 min/65°C)
- **Track Record**: 2 080 km of water main lined across North America




# ALTRA lined steel pipes ready for bending test



# CI Pipe Specimens

- Pipe F: preparing to ship Sanexen
- Pipes A, B, E & H: Useful pipes for T&A to keep
- Pipe C, D & G: Sent to developers


Pipes A-H

Pipe C and rented pipe cutter

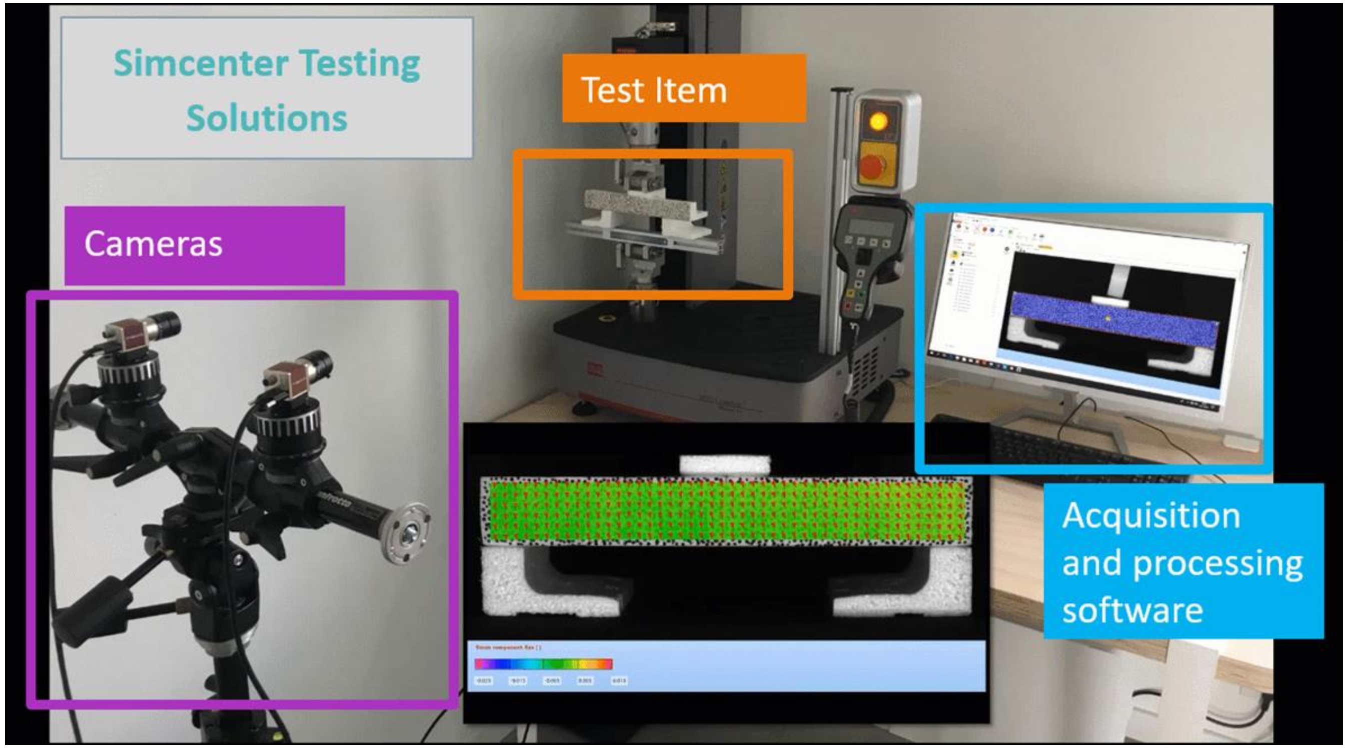

Pipe F and rented pipe cutter

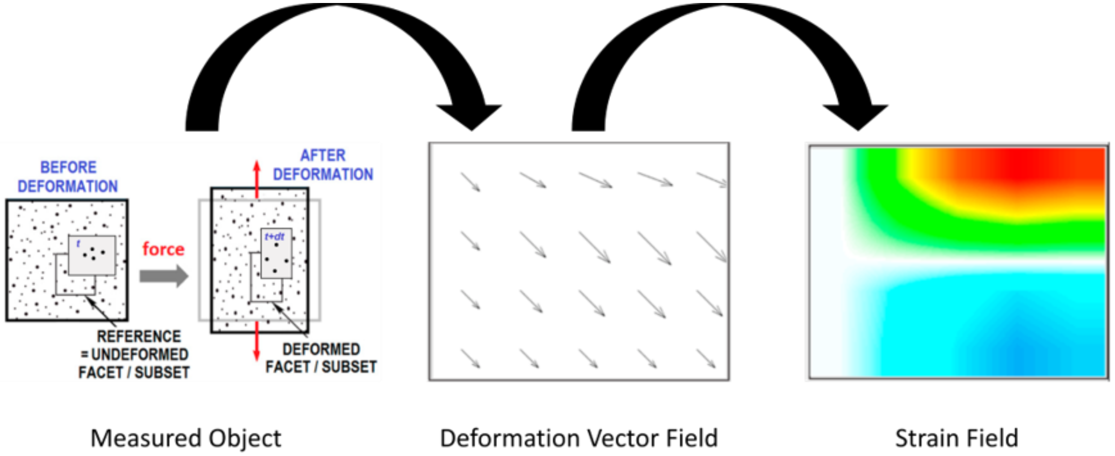

Pipe D

# PSE&G Pipes – Installed summer of 1959

# Digital Image Correlation – A 3D Solution to a 3D Problem

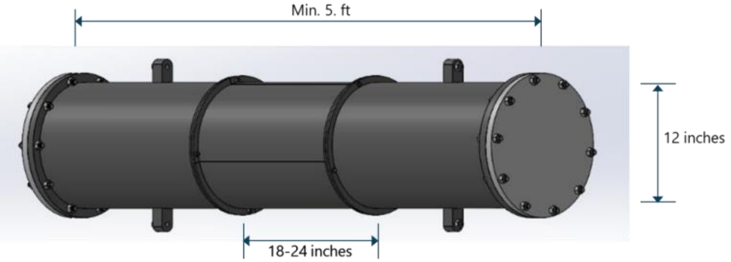
- Non-contact technique for full-field 3D strain and deformation measurement
- Tracking the points on the surface of tested object before and after deformation
- A rigorous way to validate finite element model prediction

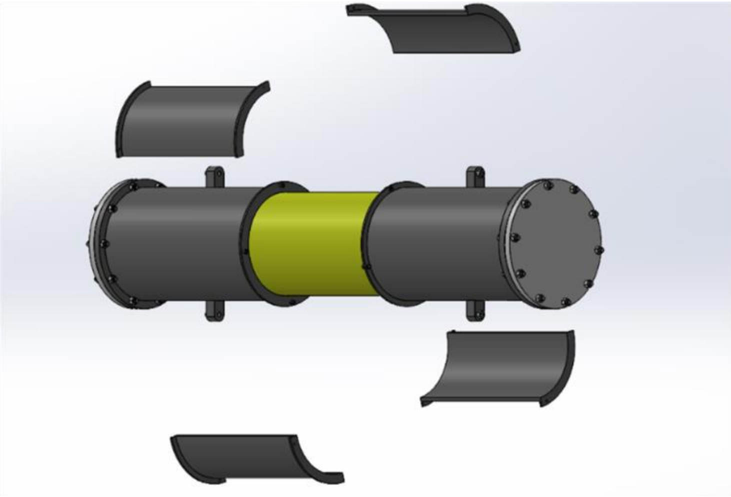


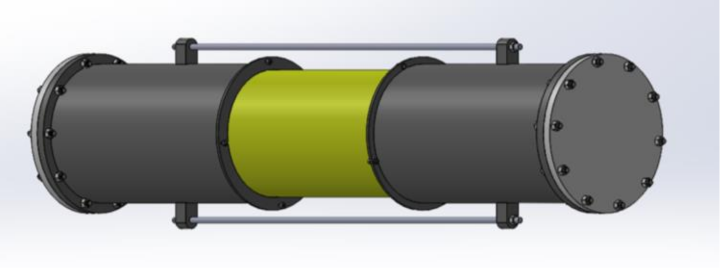



# T5: Internal Loading

| | | |
|---|---|---|
| T5.1.1. Short Term Hydrostatic Pressure Tests | ▪ 12-inch diam pipe sections, about 6 ft long. End-caps will be installed after application of the repair.<br>▪ Middle sleeves will be removed in tests to simulate deterioration of the host pipe.<br>▪ Tests are under hydrostatic pressure to failure. | ▪ 3 pipe samples/PIP.<br>▪ Pipes will be delivered to the awardees without end-caps for continuous application of the repair by awardees |
| T5.1.3 Impact Performance Test | ▪ Perform pressure test for leak on indented pipe.<br>▪ Indentation will be applied using hemispherical 1.1-lb drop weight from a height of 40-inches as per ASME standards PCC-2 Article 4.1 |  |
| T5.2 Long-Term Cyclic Pressure tests | ▪ Same configuration as in 5.1<br>▪ Tests are under cyclic loading at different ranges to identify failure load. | • 6 samples/PIP which include samples for additional tests, if needed. |



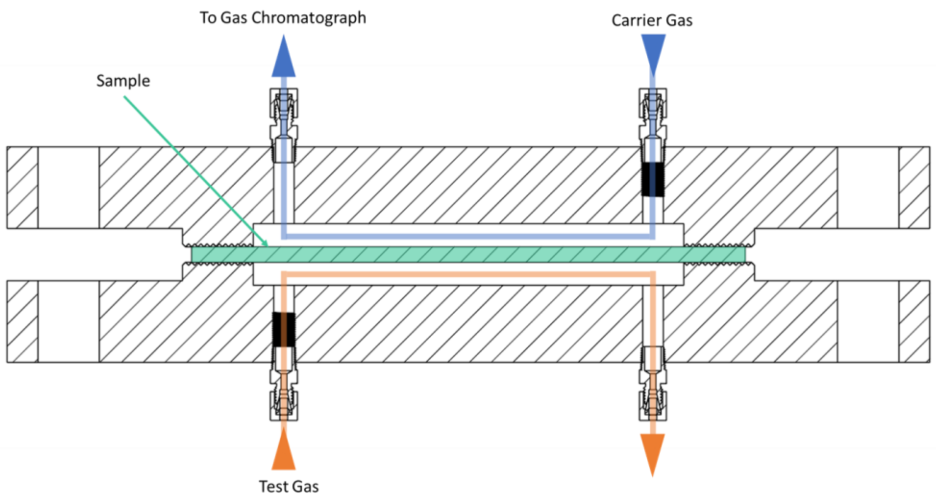





# T5: Internal Loading

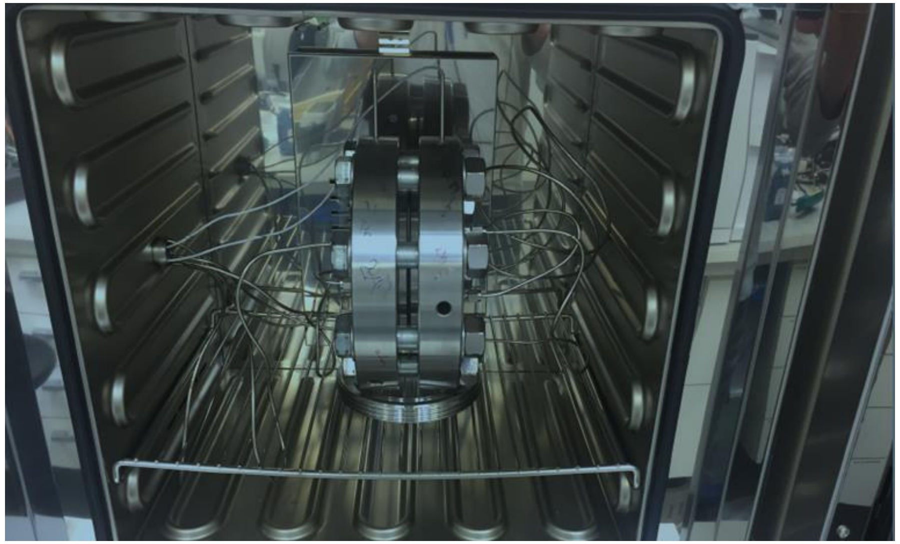
TTSP suggested hydrogen up to 20%, realistically will be 10-15%

| | | |
|---|---|---|
| T5.3 Permeability<br>T5.4 Environmental Degradation | ▪ 60-day min. exposure of typical and hydrogen-blended gas at controlled pressure and temp.<br>▪ A test sample is fixed in the middle with a constant pressure difference. Gas molecules penetrate through sample from higher pressure room into lower pressure sec. The setup will also be used to measure gas transmission rate. | ▪ Coupon samples are supplied by developers (possibly in 12-inch diam sheets). GTI will plasma cut the samples to the required testing sizes.<br>▪ In 5.4: GTI to run control tensile tests on un-exposed samples first and run the test on other samples after the exposure. |




<u>Permeation Test Notes</u>

- The test provides an estimation of the steady-state rate of transmission of a gas through the repair system.
- This test method is for the determination of (a) gas transmission rate (GTR), (b) permeance, and, in the case of homogeneous materials, (c) permeability.
- according to **ASTM D1434** Standard for Determining Gas Permeability Characteristics of Plastic Film and Sheeting.
- The sample is about 7-inch diameter supplied by the developed. Sample can be prepared on a wire mech or a highly-permeable surface and installed in the test chamber.



# Looking Forward

- NASTT, ASCE Pipelines, among other publications
- FE models sent to developers- continual communication
- Test plans have been developed for each internal and external loading test
  - Circulated with TTSP and ARPA-E -> next step is to Developers
- Refining specimen design:
  - CI vs. Steel effects on PIP performance
  - Crack width effects (steel)
  - CI Joint effects
  - Availability to consistent/appropriate CI pipe
- Targeting receipt of Developer specimens by **April 2023**
  - Working to accommodate early submission of samples
  - T&A team to provide samples for PIP deposition ~January 2023

# Questions/Discussion


**T&A Team Contact:**
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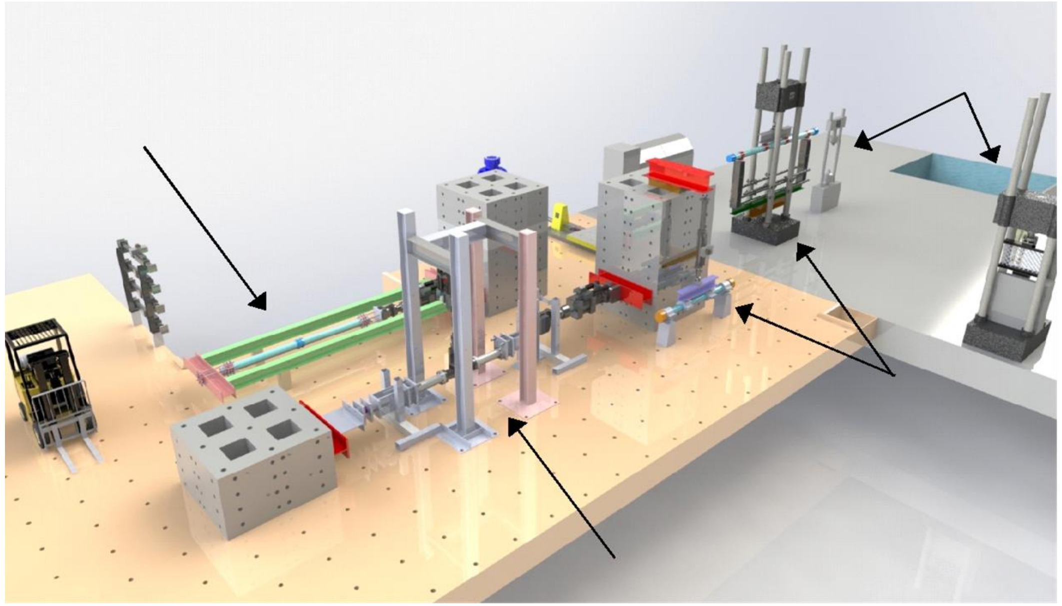
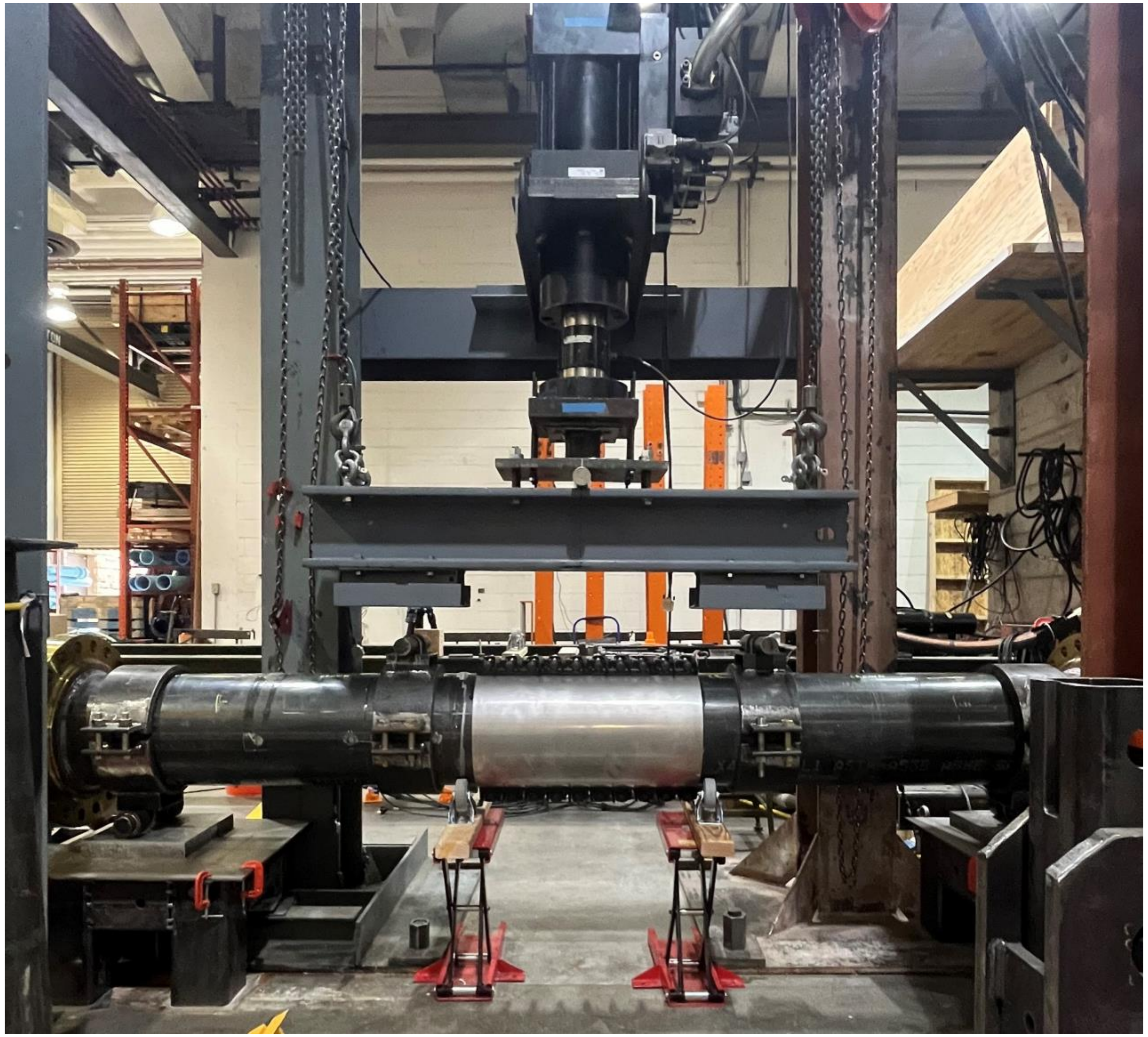
Brad Wham, PI,
Brad.Wham@Colorado.EDU

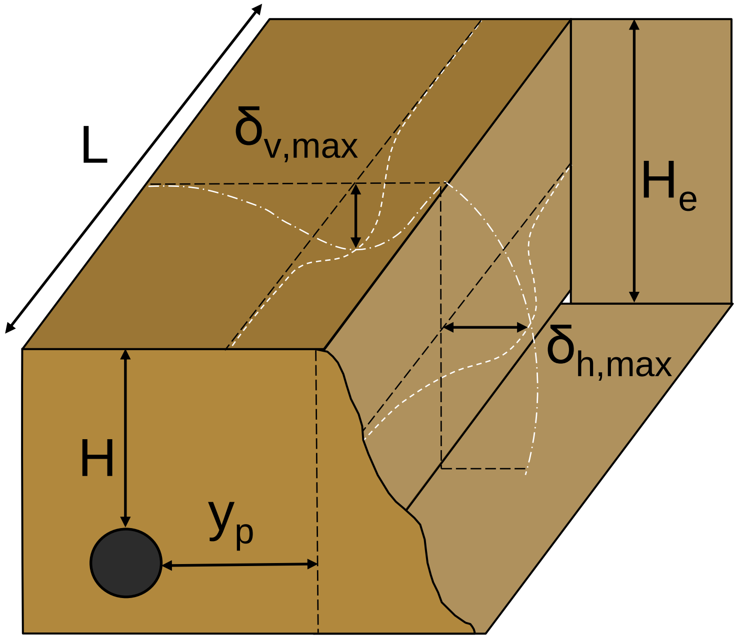



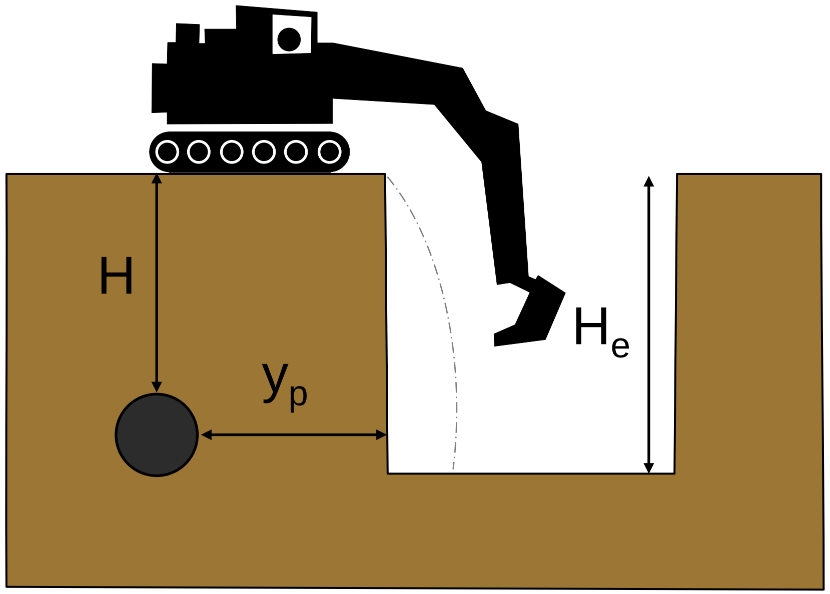


# Feedback Request – Excavation Parameters

| Primary Parameters | | | |
|---|---|---|---|
| Parameter | Minimum | Typical | Maximum |
| $y_p$ ($H_e$<5 ft) | | | N/A |
| $y_p$ ($H_e$<20 ft) | | | N/A |
| $y_p$ ($H_e$>20 ft) | | | N/A |

| Secondary Parameters | | | |
|---|---|---|---|
| Parameter | Minimum | Typical | Maximum |
| H | 2.5 ft | 3 ft | 4 ft |
| $H_e$ | | | |
| L | | | |



# TTSP Request: CI Specimen

**A.1. General characteristics:**

– 12 in. diameter (CIOD= ~13.2 in.)

– CI Class: Preference: Class B. We can accommodate thinner-walled Class A.

  - Class C and D CI have a different outer diameter (OD), and will present additional difficulties in fixturing, pressurizing, and loading (Figure A.1 provided dimensions for reference)

**A.2. Specimen characteristics**

Two potential specimen dimensions would be useful for bending only tests. (Figure A.2 provides illustrations of the test specimens)

**1. CI pipe with Joint (dia. = 12 in.):**

– Length: 10 ft of intact pipe (free of cracks) [minimum length of 9 ft]

– Joint at center (within 8 in. of center of specimen)

– Lead caulked or otherwise weak joint (not repaired or stiffened, not cemented)

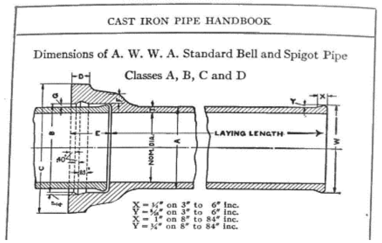
  - Stiff joints will not impose worst case deformations to the PIP, and likely result in failure of the CI pipe at the loading fixtures.

**2. Straight section of CI pipe (dia. = 12 in.):**

– 10 ft or longer intact pipe barrel (free of cracks)

– Existing bell could be cut off if at least 9 ft of competent barrel remains

– These specimens would be "cracked" at the center to represent round crack before (or perhaps after) application of PIP repair




| Nominal Diameter Inches | Class | Dimensions, Inches | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | A | B | C | D | E | F | G | T | W |
| 12 | A | 13.20 | 14.00 | 17.20 | 1.50 | 4.00 | .80 | .40 | .54 | 13.70 |
| | B | 13.20 | 14.00 | 17.20 | 1.50 | 4.00 | .80 | .40 | .62 | 13.70 |
| | C | 13.50 | 14.30 | 17.70 | 1.50 | 4.00 | .85 | .40 | .68 | 14.00 |
| | D | 13.50 | 14.30 | 17.70 | 1.50 | 4.00 | .85 | .40 | .75 | 14.00 |

**Figure A.1. Dimensions of Class A-D CI pipe (CI handbook, 1927)**

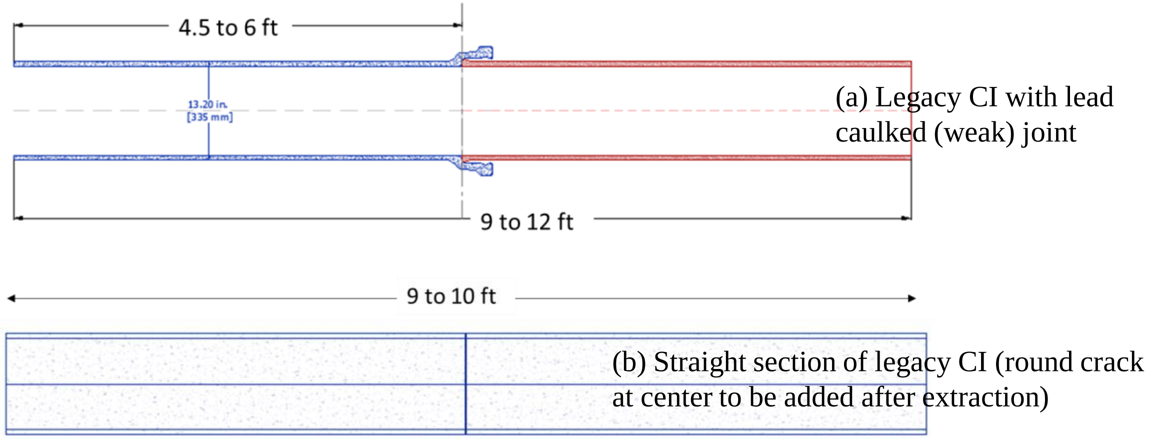



**Figure A.2. Illustrations of requested CI specimens**